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Recent Trends and Future Prospects for Structural Steel Technology Used in Buildings

Kouichirou KEIRA*(1)

1. Introduction

Over the past 40 years, the number of Japan's steel buildings have increased to levels unparalleled in the rest of the world. As shown in **Fig. 1**, steel buildings became one of the main types of construction, together with wood buildings, in the late 1980s. Steel use exceeded 5 million tons in 1970, and is estimated to have reached 12 million tons in 1990. Steel building construction has averaged about 10 million tons of steel per year in the past decade and is expected to remain at this level in the future. This level of usage accounted for 15% of the 1996 domestic carbon steel demand of about 68 million tons.

By scale, two-story and smaller buildings account for a little less than 70% of the total steel structure production, while five-story and smaller buildings account for about 93%. The total floor area per building is about 300 m^2 for most steel buildings, and steel consumption per building is about 30 tons. The average person may often equate steel buildings with superhigh-rise and large-span structures, but small-scale and low-rise buildings, constructed at an annual rate of about 300,000, require 10 million tons of steel framework.

Of the steel types used for building structures, 60% are H-shapes, 10% are cold-formed square tubes (referred to here as box columns), and the remaining 30% are plates and flat bars. The percentage of the plates used increases with the building height. Steels with a strength of 40 kgf/mm^2 account for 80% of the total building structural steel consumption.

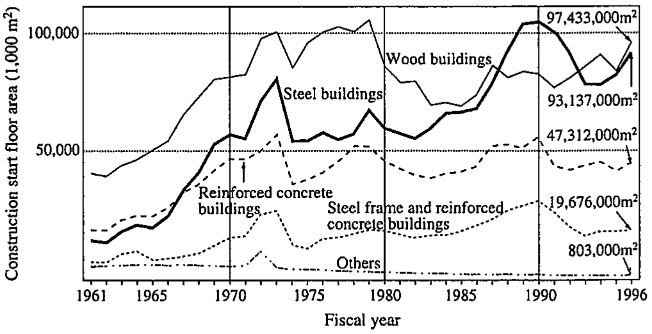

Fig. 1 Year-on-year (fiscal) change in building construction start floor area by type of construction

*(1) Construction & Architectural Materials Development & Engineering Service Div.

2. Present State of Building Structural Steels

Fig. 2 shows crude steel production, steel frame production, and the time series development of principal building structural steels. These trends can be divided into three main periods, which can be correlated with the representative types of building structural steels as follows:

I. Period of quantitative expansion (up to the early 1970s): H-shapes and box columns

II. Period of quantitative stabilization (up to the mid-1980s): None

III. Period of qualitative transition and review (from the late 1980s): High-performance steels and SN steels

2.1 Spread of H-shapes and box columns

Building structural steels during the period of quantitative expansion up to the 1970s were represented by H-shapes and box columns. H-shapes and box columns have remained the basic members for steel buildings.

Since the start of their production in 1961, H-shapes were recognized as epoch-making steel products conducive to the construction of steel-framed buildings. Material-saving design had long favored steel-frame buildings constructed by the labor-intensive assembly of angles and channels. The excellent basic performance of H-shapes and the continued effort of H-shape manufacturers, however, eventually enabled H-shapes to gain 60% of the demand for steels used in buildings, particularly for beams.

Commercial production of box columns began about 1970 and were spotlighted as column materials after the 1981 establishment in Japan of a new seismic design code. Under the code, structural simplicity and building planning freedom made rigid-frame construction for both rises and spans relatively more advantageous than braced construction. This led to the explosive spread of box columns in building construction. Box columns are now produced at an annual rate of about 1 million tons and are reported to account for 90% of columns according to one survey. Box columns have become so firmly positioned as representative columns in low- and medium-rise buildings that the use of the word "columns" brings box columns to mined.

2.2 Development and commercialization of high-performance steels

From the standpoint of expanding steel consumption in building construction, which had accounted for about a half of the domestic steel demand in the late 1980s, integrated steelmakers successively developed and commercialized steels with new performance properties and functions to meet the requirements of such cutting-edge steel structural applications as ultrahigh-rise buildings and large-span structures. The development and commercialization prospects for the new steels are concerned with seismic performance like higher or lower

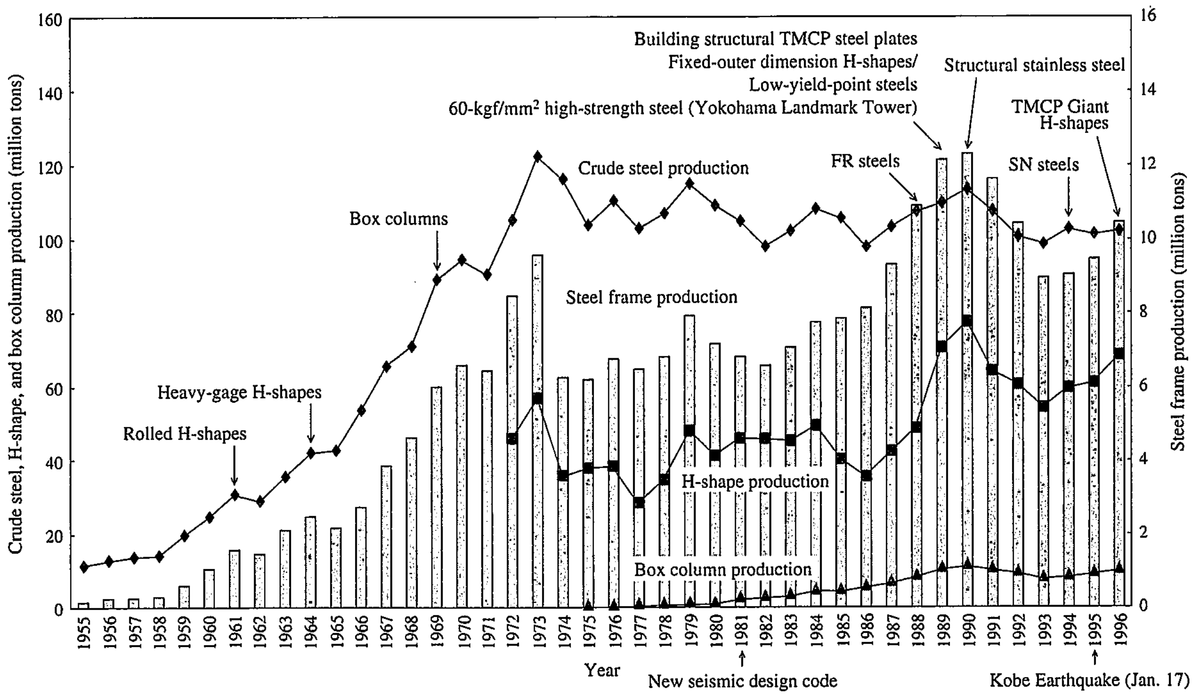

Fig. 2 Changes in building structural steel developments

yield point, lower yield ratio and narrower yield point range; fabrication and construction performance properties like weldability, and geometrical and dimensional tolerances; durability performance; and the addition of new functions. Such typical steels are described below.

(1) High-strength steels

Under the comprehensive technology development project of the Ministry of Construction, known as the comprehensive new materials project and conducted from 1988 to 1992, application research was carried out to provide 60-kgf/mm^2 high-strength steels with unique performance characteristics to ensure plastic deformation capacity in an earthquake and to establish their application technology. In September 1996, five integrated steel companies obtained the general materials approval of the Minister of Construction for these new high-strength steels. An example where such a new high-strength steel is used is shown in **Photo 1**.

(2) Low-yield point steels

Low-yield point steels are used as construction materials for devices to absorb seismic input energy to buildings, as part of the development work on seismic base isolation and vibration control technology. They feature an extremely low yield point, compared to conventional structural steels. An example of their application is shown in **Photo 2**.

(3) Building structural TMCP steels

These steels are manufactured by a thermomechanical control process (TMCP) and feature excellent weldability and strength stability despite their heavy gage. They were used first in the shipbuilding industry, and received general approval from the Minister of Construction in 1989 as a category specially targeted for building structures. Today, plates with thickness greater than 40 mm are almost all made from building structural TMCP steels. Very recently, TMCP Giant H-shapes were developed and applied along similar lines of thought. An application example is shown in **Photo 3**.

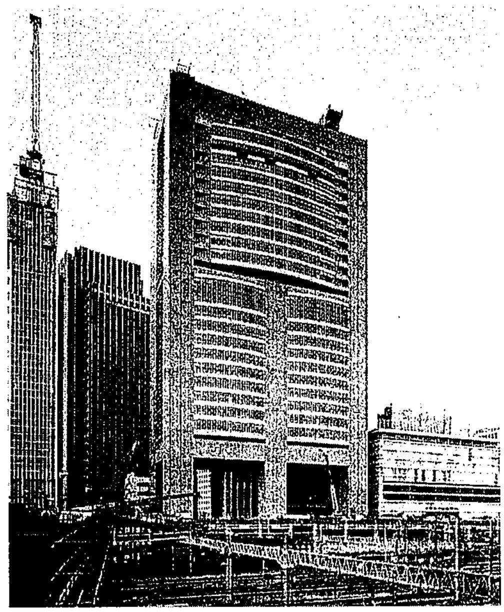

Photo 1 Application of 60-kgf/mm^2 steel (JR East Japan Headquarters Building)

(4) Fire-resistant (FR) steels

Fire-resistant steels are building structural steels developed by Nippon Steel in 1988. Alloying elements (e.g., molybdenum) that increase heat resistance are added to assure a much higher elevated-temperature strength than conventional building structural steels have. About 100,000 tons of FR steels are used annually in the construction of Multistory parkings, sports facilities, atriums, railroad station buildings, external steel frames,

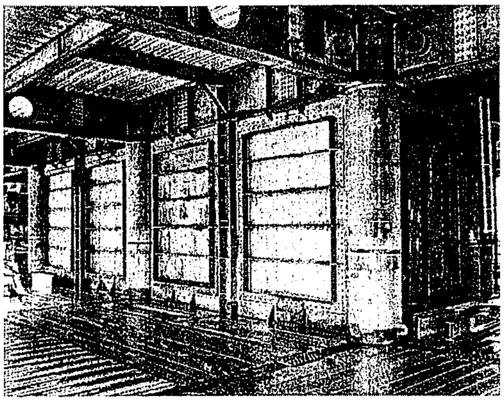

Photo 2 Seramic control wall constructed of low-yield-point steel

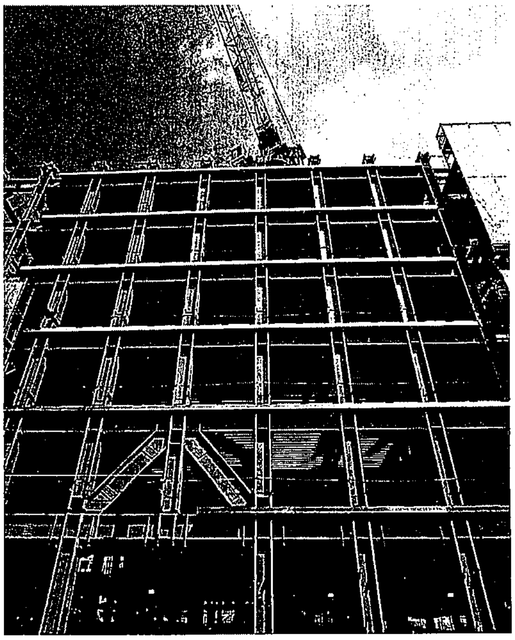

Photo 3 Giant H-shapes used as columns (Dojima Building)

and many other structures. Especially for unattended parking garages above a certain capacity, five integrated steelmakers obtained the general approval of the Minister of Construction for FR steels in February 1996. Since then, FR steels have enjoyed rapidly increasing applications. An example is shown in **Photo 4.**

(5) Building structural stainless steel

A new type of stainless steel was developed on the basis of the most popular stainless steel SUS304 (18Cr-8Ni steel) with additional properties for building structural use. It is designated PS235-SUS304 and covered by the Japan Stainless Steel Association Standard SAS 601-1993. In September 1994, the Stainless Steel Structure Builders' Association obtained the general approval of the Minister of Construction for stainless steel building structures. This association is conducting service and technology promotional activities, such as design review, fabrication shop audit, and technician certification. Some 20 stainless steel structures and buildings have already been constructed. An application example is shown in **Photo 5**.

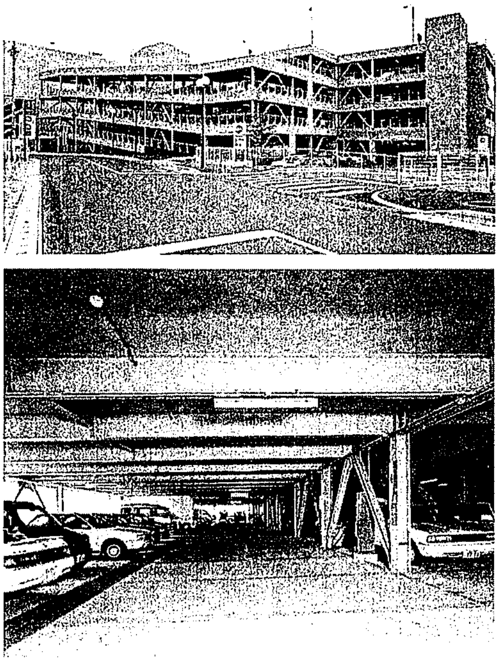

Photo 4 Multistory parking constructed of FR steel (SATY Kamimine Shop)

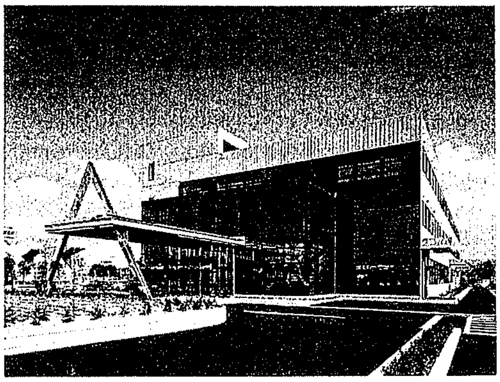

Photo 5 Stainless steel structural member (Aichi Steel Works)

(6) Fixed-outer dimension H-shapes

In 1989, Nippon Steel led the other integrated steelmakers in commercializing fixed-outer dimension H-shapes through the application of epoch-making manufacturing technology, centering on the free-control rolling of outer dimensions. This new type of H-shape has fixed outer dimensions, decreased web thickness, increased dimensional tolerances, normal plate thickness, and performance superior to that of conventional H-shapes.

2.3 Review of general-purpose structural steels (Establishment of SN steel series)

General-purpose structural steels were reviewed together with the above-mentioned steels to achieve higher performance. Rolled steels for general structures (JIS G 3101: SS) and rolled steels for welded structures (JIS G 3106: SM) had been traditionally used for steel buildings and structures. These JIS standards covered steels for general structures, including welded structures, and were based on allowable elastic stress design. Steels to be used under the new seismic design code that expects structures to absorb seismic energy by their elastoplasticity in a very large earthquake did not necessarily meet the performance requirements.

As part of the steel frame quality optimization campaign triggered by such deficient steel frame problems as steel plate ruptures, poor weld quality found in Tokyo and other areas, and improper use of mill sheets, new building structural steels with service performance characteristics specified by the new seismic design code were established as a new category, rolled steels for building structures (JIS G 3136: SN) in June 1994.

The assurance concepts of the SN standard aimed at general building steel structures may be summarized as follows:

- Weldability
- Plastic deformation capacity
- Performance commensurate with through-thickness stress
- Nominal cross-sectional dimensions
- Economy and availability
- Compatibility with international standards

A September 1994 Ministry of Construction Notification positioned the steels covered by JIS G 3136 as building structural steels. The Kobe Earthquake of January 17, 1995 led to calls for integrating all building structural steels into the SN steel standard, but it was decided to review them amid the introduction of a performance-based standard design system.

"Structural Requirements of Buildings", published in December 1997, was revised to incorporate the performance requirements of steels (virtually the same as the performance requirements of the SN steel standard). This publication is now widely disseminated to promote the application of the Grade SN building structural steels (refer to **Table 1**).

To meet the main purpose of the SN steel standard, new standards were established for round steel tubes and bars. These are JIS G 3475, Carbon Steel Tubes for Building Structures (STKN), and JIS G 3138, Steel Bars for Building Structures (SNR). Both published in October 1996, they form a series of building structural steel standards (SN standard series) together with those mentioned above.

Table 1 Main provisions of SN standard

Steel	Plate thickness (mm)	40 kgf/mm^2 (400 N/mm^2) steel	50 kgf/mm^2 (490 N/mm^2) steel
A	6 to 100	Similar to conventional SS grade, but upper limit of carbon set at 0.24 %	———
B	6 to 100	• Yield point range: 120 N/mm^2 (max.) for plate thickness over 12 mm, except for shapes with web thickness under 9 mm • Yield ratio: 80 % (max.) for plate thickness over 12 mm, and 85 % (max.) for shapes with web thickness under 9 mm • Charpy absorbed energy: 27 J (min.) for plate thickness over 12 mm • Ceq and P_{CM}: Specify either one • Upper limit of sulfur content: 0.015 % (max.) • Other: Ultrasonic testing may be specified as optional requirement for plate thickness of 13 mm (min.)	
C	16 to 100	Same requirements as steel B, plus: • Reduction of area in z-direction: 25 % (min.) • Upper limit of sulfur content: 0.008 % (max.) • Other: Ultrasonic testing	

Since 1990, technical data on box columns had been accumulated through experimental research on box columns, led mainly by the Box Column Committee of the Kozai Club. Based on the results of this research, the Kozai Club standards were established for BCR and BCP building structural cold-formed square steel tubes in July 1995, and were granted general approval by the Minister of Construction.

The yield point of the BCR grade was revised to a range of 235 to 295 N/mm^2 befitting the actual situation, considering the rise in the yield point and yield ratio with cold working. The chemical composition of BCR was specified to be similar to that of the SN standard to ensure weldability. Especially to mitigate age hardening (increase in hardness and brittleness with the lapse of time after cold working), the upper limit of the nitrogen content was additionally established. For dimensions and geometry, the lower thickness tolerance was made closer, and the curvature radius of corners was made uniform for fabrication convenience.

In September 1996, the Building Center of Japan published the "Manual for Design and Construction of Cold-Formed Square Steel Tubes for Building Structures". Cold-formed square steel tubes are now finding increased usage in building structures.

3. Future of Building Structural Steels

The Kobe Earthquake of January 17, 1995 was the first earthquake that caused devastating damage to steel buildings in Japan and left technical problems for the whole steel frame production process, from design to construction.

For example, the brittle fracture of heavy-gage large-section members originating near welded connections came to the surface for the first time in an earthquake. This is a technical area to which the results of conventional fracture mechanics cannot be directly applied and is a technical problem that must be solved in the long term. The establishment of practical measures against the failure of the column-beam welded joints that are in widespread use and the extensive damage of welds is a short-term challenge.

The government, industry, and academia have already started activities to solve these technical problems across diverse fields, including building construction, steel manufacturing, welding, and fracture mechanics. This process will identify needs for new building structural steels and related materials like welding materials, and will plant the seed for future development. A bolted column-beam connection system (designated the hyper frame system) under development or application is expected to offer one solution to the above problems in place of conventional welded structures.

4. Conclusions

A major revision of the Building Standards Law was submitted to the Diet in March 1998 to accomplish decontrol of building standards, international standard compliance, and higher safety of buildings, among other things. The Building Standards Law is about to change from conventional prescriptive standards to new performance standards.

The design system under the new Building Standards Law with performance-based requirements will call on design engineers to achieve rational and economical building steel structures by adequately employing the characteristics and performance of building structural steels and using the right steels in the right applications. It will also call on steel manufacturers to develop and supply steels to meet a variety of service performance requirements.